The Off-Plane X-ray Grating Spectrometer (OP-XGS) Technology Development Roadmap

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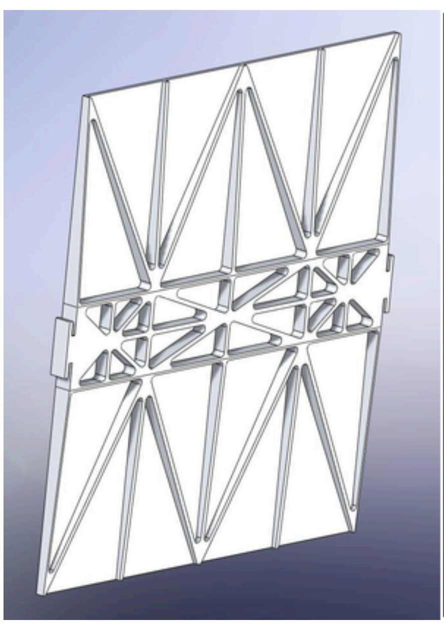
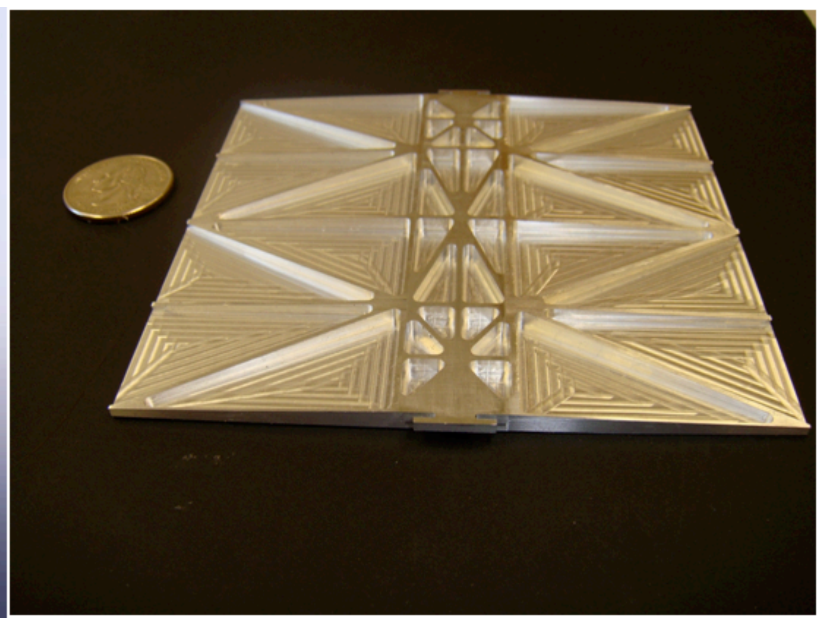



Prior and current technology development activities

The technology development roadmap for the X-ray Grating Spectrometer (XGS) requires developing high throughput, high spectral resolution grating arrays in parallel with the development of a high frame rate, high efficiency CCD device. Currently, as described in Table 1, the Off-Plane XGS (OP-XGS) reflection gratings are at a TRL of 3, and as stated below, will reach TRL of 4 as soon as laboratory testing is completed later this year.

Table 1: OP-XGS TRL 3 justification

TRL	Definition	Hardware Description	Exit Criteria
3	Analytical and experimental critical function and/or characteristic proof of concept.	Analytical studies place the technology in an appropriate context and laboratory demonstrations, modeling and simulation validate analytical prediction.	Documented analytical/experimental results validating predictions of key parameters.
	Off-Plane Reflection Grating Technology Assessment		
3	Theoretical calculations give dispersion efficiency >50% sum of orders (including Au reflection). 40% sum of orders has been obtained empirically for a radial, blazed, high density grating. Given the current design, 40% sum of orders efficiency equates to >1000 cm^2 over the bandpass. Theoretical resolution at 1 keV in 3rd order is ~9000. We have obtained an empirical resolution of > 200 at 1keV with a 3' telescope. Projection to a 5" telescope gives a extrapolated resolution of 7200. The spectral resolution requirement is >3000 over the bandpass.	• A combination of analytical predictions and laboratory demonstrations shows that Off-plane gratings are capable of obtaining the performance requirements for IXO. • Tests were performed in a relevant environment in terms of temperature and vacuum with X-rays, but vibration tests have not been performed. • A prototype grating (low fidelity component) has been fabricated but not tested.	Experimental results verify analytical predictions and validate the concept for the key IXO XGS performance requirements.


Figure 1: The XMM Reflection Grating Spectrometer

Reflection gratings have considerable heritage and are currently being employed in the Reflection Grating Spectrometer (RGS) onboard XMM-Newton (figure 1). The XMM RGS shares many characteristics with the baseline design for the IXO OP-XGS. XMM utilizes 182 gratings measuring 10 x 20 cm with thin trapezoidal substrates, variable line spacing on the grating groove profile, similar grating substrate material, and a similar alignment scheme. Off-plane reflection gratings have been flown on sounding rocket missions, most recently the Cygnus X-ray Emission Spectroscopic Survey (CyXESS) in 2006. This payload incorporated 134 off-plane gratings in two separate arrays (figure 2). The groove density was similar to that of the baseline IXO design, but the gratings were thinner and had a slightly different mount.

Prototype gratings have been fabricated and tested for IXO. The flight groove profile will be radial to match the convergence of the telescope beam, blazed at ~12° to obtain the appropriate grating efficiency, and have a groove density of 5500 grooves/mm to obtain adequate dispersion and therefore resolution. A radial, blazed, high density prototype grating (U3787) has already undergone X-ray efficiency and resolution testing. This grating was fabricated by HORIBA Jobin-Yvon for IXO. The grating has a radial profile to match a 0.9 m telescope focus, a groove density of 4246 grooves/mm, and a blaze angle of 9°. Longer telescope foci, higher groove densities, and shallower blaze angles are the technical difficulties encountered when producing flight gratings. This particular test grating (U3787) addresses the issue of shallow blaze angle while having a modest groove density and modest radial profile. Other test gratings have addressed the issue of high groove density with a blaze (U3731 has a groove density of 5870 grooves/mm at a blaze of 16° without a radial convergence) while other gratings have addressed the issue of a longer telescope focus (62636 is a radial groove grating matching a 8 m telescope convergence with a density of 4500 grooves/mm and large format of 106 x 106 mm). X-ray testing of U3787 demonstrated an absolute efficiency of 40.5% in dispersed orders at 1.25 keV (McEntaffer et al, 2004, Proc. SPIE, 5168, 492). We use this number as a requirement driver for our baseline design, i.e. the effective area of the gratings equals the geometric collecting area multiplied by 40%. U3787 was also tested for resolution (Osterman et al, 2004, SPIE, 5488, 302) and exhibited a spectral resolution of 205 ($\lambda/\Delta\lambda$) for 10th order Cu-L (0.9 keV) using a 3 arc minute telescope in the finite conjugate. Absence of line broadening showed that the test was telescope limited. Scaling to a 5 arc second telescope gives a scaled spectral resolution of 7380, assuming that telescope aberrations continue to dominate over grating aberrations. Therefore, this low-fidelity grating has demonstrated efficiency and scalable resolution that are consistent with IXO XGS performance requirements.

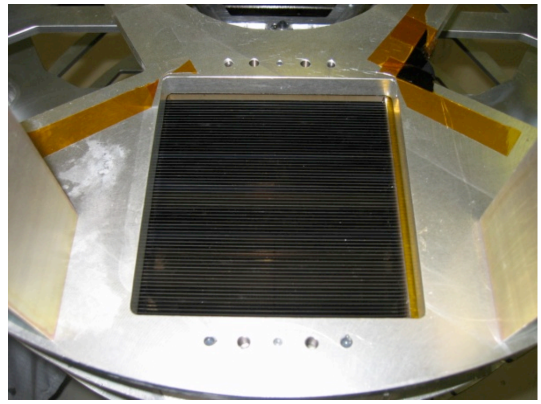


Figure 2: One of the two grating arrays onboard CyXESS.

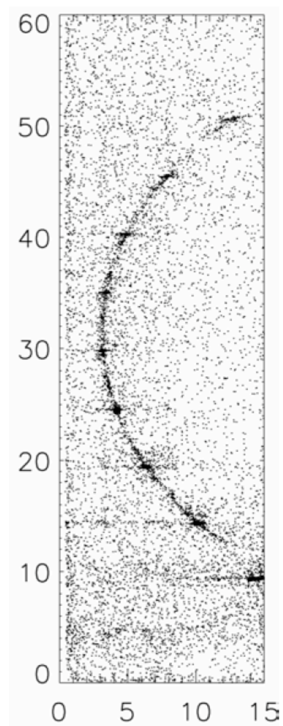


Figure 3: Off-plane diffraction arc from the U3787 prototype grating.

The major milestones to achieve TRL 6 for an off-plane reflection grating spectrometer are driven by those of the gratings as the CCDs have already achieved a high TRL with significant heritage.

TRL milestones and schedule

The key milestones for the technology development of off-plane gratings to TRL 6 include:

- Fabrication and testing of a flight prototype grating: A reflection grating with a flight prototype groove profile (grating 62636) has been fabricated and is currently undergoing X-ray testing (figure 4). Efficiency tests are ongoing at the University of Colorado and are planned to be verified at a new test facility at the University of Iowa. Resolution tests are planned for the fourth quarter of calendar year 2009 at the Goddard Space Flight Center X-ray beamline. The groove convergence angle on the prototype grating was made to match that of the IXO test optics. This will result in a telescope limited system capable of approaching flight resolution requirements. **Verifying flight requirements on this low fidelity grating will bring the TRL up to 4 before the end of 2009**.
    - Place IXO low fidelity prototype grating into the beam of IXO telescope optics at GSFC's X-ray beamline facility. This will demonstrate resolution requirements at the low fidelity level. (4th quarter 2009)
    - An X-ray test facility at the University of Iowa will be completed during the 3rd quarter of 2009 with subsequent grating efficiency tests on the prototype grating. (4th quarter 2009)

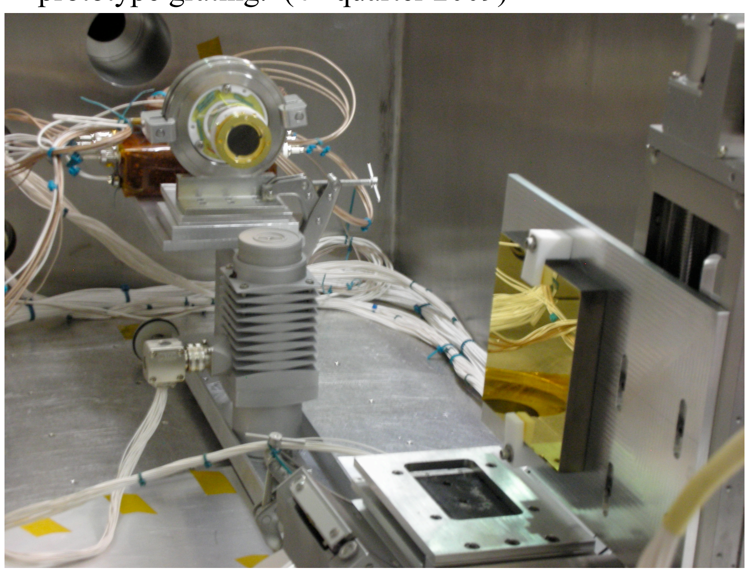


Figure 4: Grating 62636 in the University of Colorado X-ray test facility

- Environmental & X-ray testing of a flight-like grating mounted in a flight-like module: A grating exhibiting a flight-like profile will be mounted into a flight-like module to provide a medium fidelity subsystem component that will be capable of demonstrating overall performance with realistic support elements. The grating substrate will be fabricated from Be and match the flight grating in every way including weight, size, and flatness. This fabrication process was initiated by LAGauge in the third quarter of 2009. These flight-like substrates will be available for grating replication. Other flight-like substrates have already been fabricated at the University of Iowa from Al (figure 5) and will be used as engineering units. In order to increase the fidelity of the groove profile on the replicas, existing etching equipment will be upgraded to accommodate the larger format substrates, thus providing a radial, blazed grating similar to what will be required for flight. **Verifying flight requirements on this medium fidelity grating and mount will bring the TRL up to 5 at the beginning of 2011.**

- Fabricate flight grating substrates. (3^{rd} - 4^{th} quarter 2009)
- Upgrade existing etching equipment for larger format gratings. (1^{st} quarter 2010 – 2^{nd} quarter 2010)
- Fabricate new master grating. (2^{nd} quarter 2010 – 3^{rd} quarter 2010)
- Replicate prototype grating onto flight substrates. (3^{rd} quarter 2010)
- Fabricate a single grating module. (1^{st} quarter 2010 – 3^{rd} quarter 2010)
- Environmental & X-ray testing of medium fidelity grating within a grating mount. (4^{th} quarter 2010 – 1^{st} quarter 2011)

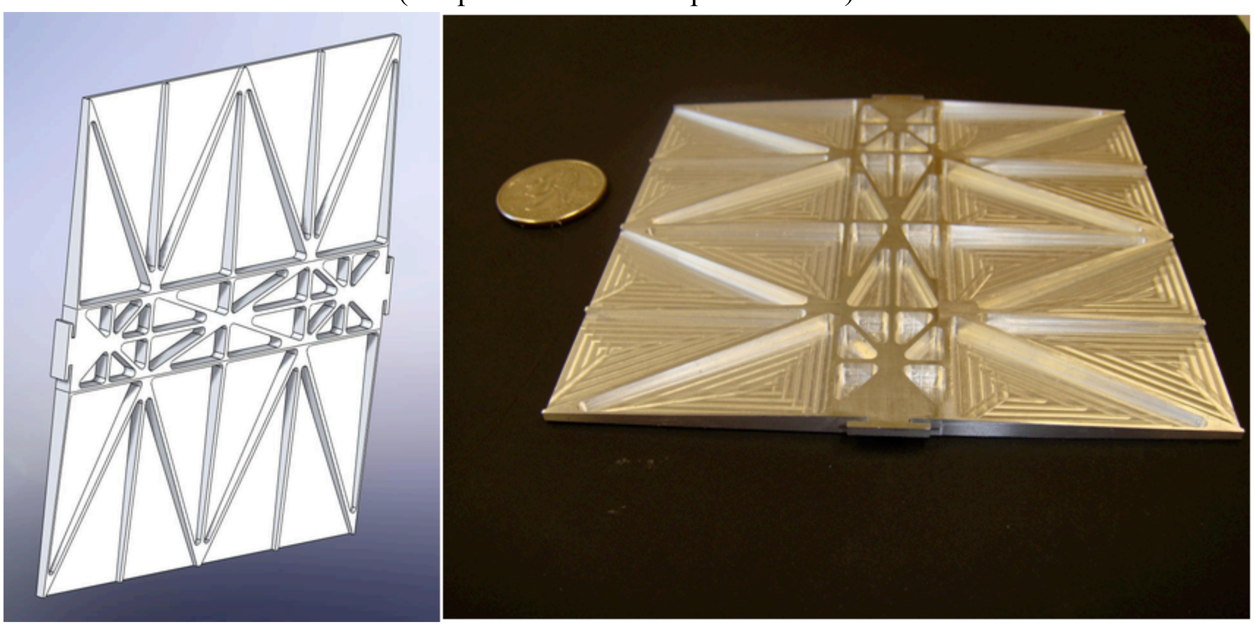


Figure 5: Left - CAD model of a single IXO flight grating. Right - Aluminum substrate fabricated at University of Iowa.

- Demonstration of an aligned flight-like module: Following TRL 5 development, an appropriate first step to developing a full module is partially filling a flight module with medium fidelity gratings to formulate an alignment strategy and place constraints on grating fabrication/replication that are consistent with subsequent optical alignment. Developing a fully aligned flight-like module (figure 6) requires development of a method to efficiently reproduce high quality gratings onto flight substrates. These high fidelity gratings will then be mounted into a single module to verify the alignment strategy. Five of these gratings spaced across the module will be adequate to ensure proper alignment. The remaining slots will be filled with mass models. The spectrum from each grating surface will overlap at the focal plane while maintaining the spectral resolution requirement. The aligned module will undergo environmental tests, X-ray efficiency tests and spectral resolution tests. Resolution tests pre and post vibration testing will verify the mounting and alignment strategies. **Empirical verification of analytic predictions made for this high fidelity assembly will increase the TRL to 6. Plans put completion of this effort before the end of 2012.**

- Perform alignment test on 3 prototype gratings within module. Formulate alignment strategy and fabrication requirements leading to optical alignment. (1st quarter 2011 – 4th quarter 2011)
- Optimizing etching quality of existing grating masters. (1st quarter 2011 – 4th quarter 2011)
  - Recording different resin layer characteristics
  - Study of multiple etching properties to preserve microroughness
- Fabricate a high fidelity master grating (3rd quarter 2011 – 4th quarter 2011)
- Replication of grating profiles matching flight requirements onto flight substrates. (1st quarter 2012 – 2nd quarter 2012)
- Environmental and X-ray testing of flight-like gratings within a flight-like module. (2nd quarter 2012 – 4th quarter 2012)

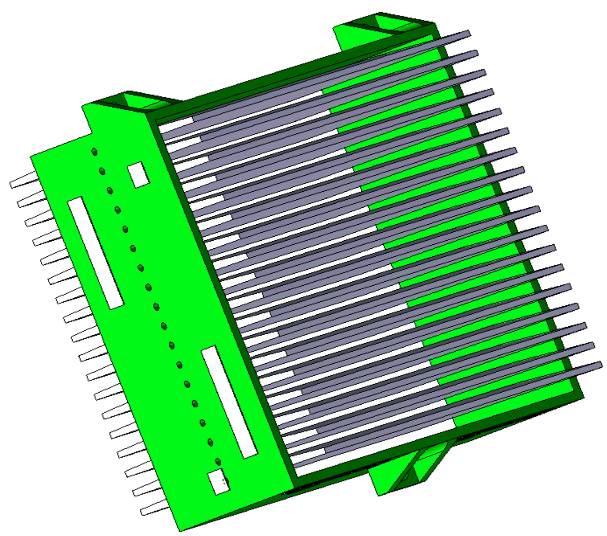


Figure 6: CAD model of a fully populated grating module.

- Grating array engineering unit: After completion of TRL 6 we plan to fabricate a grating array engineering unit during flight development. This unit will consist of the array mounting platform and a series of the populated flight-like modules described above. The final flight array consists of 30 fully populated flight modules (18 gratings per module, figure 7). The engineering unit will undergo environmental and X-ray testing.

This will be achieved prior to the end of calendar year 2013 in preparation for the PDR in 2014.

- Fabrication of flight-like grating array support structure. (4th quarter 2011 – 3rd quarter 2012)
- Populate array with an adequate number of flight like grating modules to verify module-to-module alignment. Fill remaining space with mass models. (2nd quarter 2012 – 2nd quarter 2013)
- Environmental and X-ray testing of the complete array to demonstrate performance requirements and alignment technique. (2nd quarter 2013 – 4th quarter 2013)

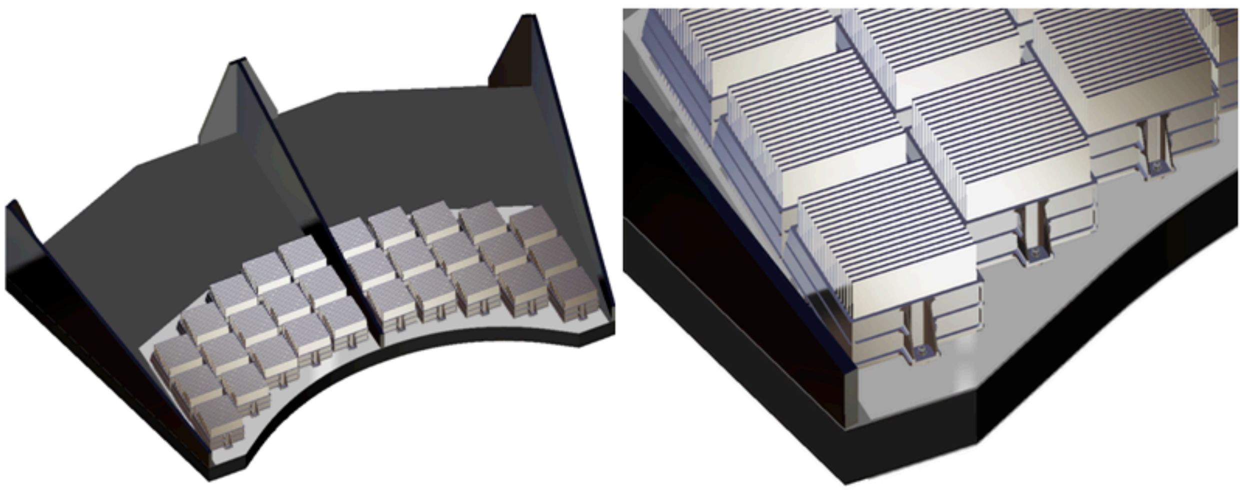
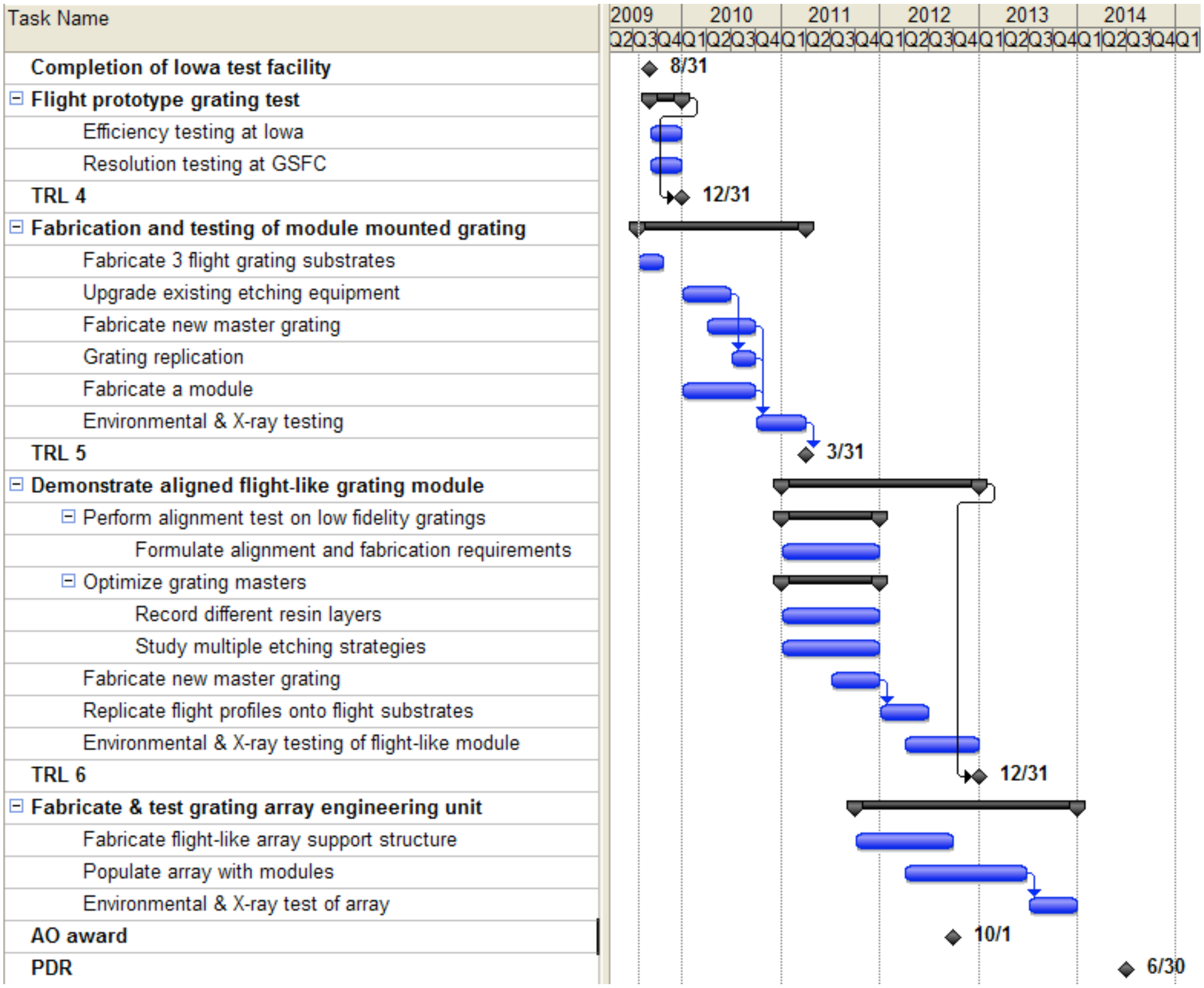


Figure 7: CAD model of a fully populated Off-Plane Grating Array. The close-up image (right) shows individual module detail.

Schedule


Task Name
2009
2010
2011
2012
2013
2014
Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1
Completion of Iowa test facility
8/31
Flight prototype grating test
Efficiency testing at Iowa
Resolution testing at GSFC
TRL 4
12/31
Fabrication and testing of module mounted grating
Fabricate 3 flight grating substrates
Upgrade existing etching equipment
Fabricate new master grating
Grating replication
Fabricate a module
Environmental & X-ray testing
TRL 5
3/31
Demonstrate aligned flight-like grating module
Perform alignment test on low fidelity gratings
Formulate alignment and fabrication requirements
Optimize grating masters
Record different resin layers
Study multiple etching strategies
Fabricate new master grating
Replicate flight profiles onto flight substrates
Environmental & X-ray testing of flight-like module
TRL 6
12/31
Fabricate & test grating array engineering unit
Fabricate flight-like array support structure
Populate array with modules
Environmental & X-ray test of array
AO award
10/1
PDR
6/30